(72) Inventors; and
(75) Inventors/Applicants (for US only): ELLINGSRUD, Svein [NO/NO]; Tyholt alle 9A, N-7052 Trondheim (NO). EIDESMO, Terje [NO/NO]; Markapl. 5, N-7054 Ranheim (NO). KONG, Fan-Nian [NO/NO]; Langbolgen 71, N-1150 Oslo (NO). WESTERDAHL, Harald [NO/NO]; Haugeras, N-2072 Dal (NO).

[Continued on next page]

(54) Title: METHOD AND APPARATUS FOR DETERMINING THE NATURE OF SUBTERRANEAN RESERVOIRS
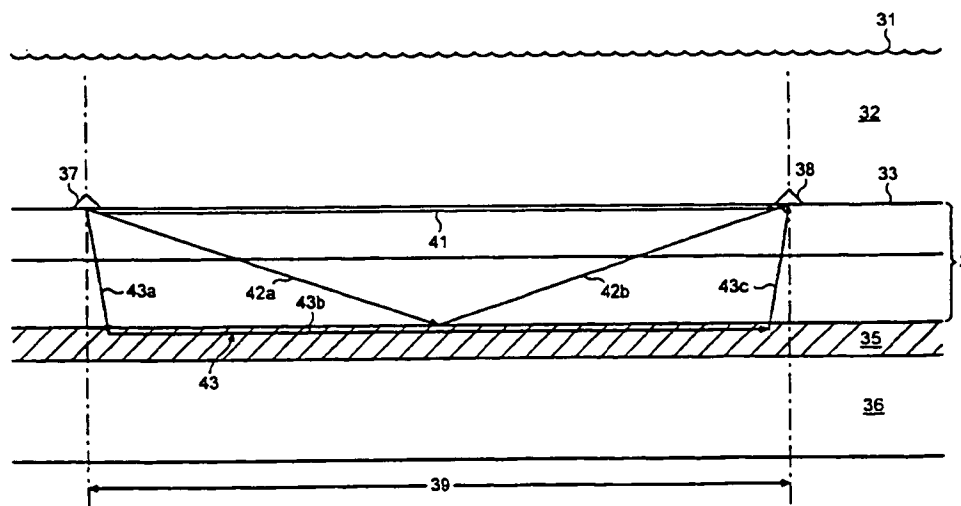
(57) Abstract: A system for detecting a subterranean reservoir or determining the nature of a subterranean reservoir (35) whose position and geometry is known from previous seismic surveys. An electromagnetic field (42, 43) is applied by a transmitter (37) on the seabed (33) and detected by antenna (38) also on the seabed (33). A refracted wave component (43, 43c) is sought in the wave field response, to determine the nature of any reservoir present.

2

Method and Apparatus for Determining
the Nature of Subterranean Reservoirs

The present invention relates to a method and
apparatus for determining the nature of submarine and
subterranean reservoirs. The invention is particularly
suitable for determining whether a reservoir, whose
approximate geometry and location are known, contains
hydrocarbons or water, though it can also be applied to
detecting reservoirs with particular characteristics.

Currently, the most widely used techniques for
geological surveying, particularly in sub-marine
situations, are seismic methods. These seismic techniques
are capable of revealing the structure of the subterranean
strata with some accuracy. However, whereas a seismic
survey can reveal the location and shape of a potential
reservoir, it cannot reveal the nature of the reservoir.

The solution therefore is to drill a borehole into
the reservoir. However, the costs involved in drilling an
exploration well tend to be in the region of £25m and
since the success rate is generally about 1 in 10, this
tends to be a very costly exercise.

It is therefore an object of the invention to provide
a system for determining, with greater certainty, the
nature of a subterranean reservoir without the need to
sink a borehole.

According to one aspect of the invention, there is
provided a method of determining the nature of a
subterranean reservoir whose approximate geometry and
location are known, which comprises: applying a time
varying electromagnetic field to the strata containing the
reservoir; detecting the electromagnetic wave field
response; seeking in the wave field response, a component
representing a refracted wave from the hydrocarbon layer;

3

2

and determining the content of the reservoir, based on the presence or absence of a wave component refracted by the hydrocarbon layer.

According to a second aspect of the invention, there is provided a method for searching for a hydrocarbon containing subterranean reservoir which comprises: applying a time varying electromagnetic field to subterranean strata; detecting the electromagnetic wave field response; seeking, in the wave field response, a component representing a refracted wave; and determining the presence and/or nature of any reservoir identified based on the presence or absence of a wave component refracted by hydrocarbon layer.

According to a further aspect of the invention, there is provided apparatus for determining the nature of a subterranean reservoir whose approximate geometry and location are known, or for searching for a hydrocarbon containing subterranean reservoir, the apparatus comprising: means for applying a time varying electromagnetic field to the strata containing the reservoir; means for detecting the electromagnetic wave field response; and means for seeking, in the wave field response, a component representing a refracted wave, thereby enabling the presence and/or nature of a reservoir to be determined.

It has been appreciated by the present applicants that while the seismic properties of oil-filled strata and water-filled strata do not differ significantly, their electromagnetic resistivities (permittivities) do differ. Thus, by using an electromagnetic surveying method, these differences can be exploited and the success rate in predicting the nature of a reservoir can be increased significantly. This represents potentially an enormous cost saving.

The present invention arises from an appreciation of
the fact that when an EM field is applied to subterranean
strata which include a reservoir, in addition to a direct
wave component and a reflected wave component from the

5   reservoir, the detected wave field response will include a
" refracted" wave component from the reservoir. The
reservoir containing hydrocarbon is acting in some way as
a wave guide. For the purposes of this specification,
however, the wave will be referred to as a " refracted

10   wave" , regardless of the particular mechanism which in
fact pertains.

Be that as it may, a refracted wave behaves
differently, depending on the nature of the stratum in
which it is propagated. In particular, the propagation

15   losses in hydrocarbon stratum are much lower than in a
water-bearing stratum while the speed of propagation is
much higher. Thus, when an oil-bearing reservoir is
present, and an EM field is applied, a strong and rapidly
propagated refracted wave can be detected. This may

20   therefore indicate the presence of the reservoir or its
nature if its presence is already known. Preferably,
therefore, the method according to the invention further
includes the step of analyzing the effects on any detected
refracted wave component that have been caused by the

25   reservoir in order to determine further the content of the
reservoir based on the analysis.

Preferably, the applied electromagnetic field is
polarized. Preferably, the polarization is such as if
created by in-line horizontal transmitter and receiver

30   antennas.

If the offset between the transmitter and receiver is
significantly greater than three times the depth of the
reservoir from the seabed (i.e. the thickness of the

5

overburden), it will be appreciated that the attenuation
of the refracted wave will often be less than that of
direct wave and the reflected wave. The reason for this is
the fact that the path of the refracted wave will be
5   effectively distance from the transmitter down to the
reservoir i.e. the thickness of the overburden, plus the
offset along the reservoir, plus the distance from the
reservoir up to the receivers i.e. once again the
thickness of the overburden.

10   The polarization of the source transmission will
determine how much energy is transmitted into the
oil-bearing layer in the direction of the receiver. A
dipole antenna is therefore the preferred transmitter,
though any transmitter capable of generating an
15   appropriate polarized field can be used. In general, it is
preferable to adopt a dipole with a large effective
length. The transmitter dipole may therefore be 100 to
1000 meters in length , and may be 10 to 1000 meters
preferably cross-polarized. The receiver Dipole optimum
20   length is determined by the thickness of the overburden.

The technique is applicable in exploring land-based
subterranean reservoirs but is especially applicable to
submarine, in particular sub-sea, subterranean reservoirs.
Preferably the field is applied using one or more
25   transmitters located on the earth's surface, and the
detection is carried out by one or more receivers located
on the earth's surface. In a preferred application, the
transmitter(s) and/or receivers are located on or close to
the seabed or the bed of some other area of water.
30   Conveniently, there will be a single transmitter and an
array of receivers, the transmitter(s) and receivers being
dipole antennae or coils, though other forms of
transmitter/receivers can be used. The transmitter may be
in an existing well. Also, if improved directionality of

6

the emitted field is desirable, then a plurality of
transmitters with phase adjustment can be used.

In one arrangement, a single transmitter and several
receivers are arranged on a single cable which is laid in
5   the required position on the seabed by a surface or
submarine vessel. These can then be moved to another
location. In a second arrangement, several receivers have
fixed positions on the seabed. The transmitter can be
moved to different locations. In a third arrangement, a
10   transmitter may be positioned by a first vessel while a
second vessel positions one or more receivers. This
affords flexibility in the positioning of both transmitter
and receivers. In a fourth arrangement, that the
transmitter be in an existing well while the receivers may
15   constitute a fixed matrix or they may be movable.

It will be appreciated that the present invention may
be used to determine the position, the extent, the nature
and the volume of a particular stratum, and may also be
used to detect changes in these parameters over a period
20   of time.

Electromagnetic surveying techniques in themselves
are known. However, they are not widely used in practice.
In general, the reservoirs of interest are about 1 km or
more below the seabed. In order to carry out
25   electromagnetic surveying as a stand alone technique in
these conditions, with any reasonable degree of
resolution, short wavelengths are necessary.
Unfortunately, such short wavelengths suffer from very
high attenuation. Long wavelengths do not provide
30   adequate resolution. For these reasons, seismic
techniques are preferred.

However, while longer wavelengths applied by
electromagnetic techniques cannot provide sufficient
information to provide an accurate indication of the

boundaries of the various strata, if the geological
structure is already known, they can be used to determine
the nature of a particular identified formation, if the
possibilities for the nature of that formation have
significantly differing electromagnetic characteristics.
The resolution is not particularly important and so longer
wavelengths which do not suffer from excessive attenuation
can be employed.

The resistivity of seawater is about 0.3 ohm-m and
that of the overburden beneath the seabed would typically
be from 0.3 to 4 ohm-m, for example about 2 ohm-m.
However, the resisitivty of an oil reservoir is likely to
be about 20-300 ohm-m. This large difference can be
exploited using the techniques of the present invention.
Typically, the resisitvity of a hydrocarbon-bearing
formation will be 20 to 300 times greater than water-
bearing formation.

Due to the different electromagnetic properties of a
gas/oil bearing formation and a water bearing formation,
one can expect a reflection and refraction of the
transmitted field at the boundary of a gas/oil bearing
formation. However, the similarity between the properties
of the overburden and a reservoir containing water means
that no reflection or refraction is likely to occur.

The transmitted field may be pulsed, however, a
coherent continuous wave with stepped frequencies is
preferred. It may be transmitted for a significant period
of time, during which the transmitter should preferably be
stationary (although it could be moving slowly), and the
transmission stable. Thus, the field may be transmitted
for a period of time from 3 seconds to 60 minutes,
preferably from 3 to 30 minutes, for example about 20
minutes. The receivers may also be arranged to detect a
direct wave and a wave refracted from the reservoir, and

8

the analysis may include extracting phase and amplitude
data of the refracted wave from corresponding data from
the direct wave.

Preferably, the wavelength of the transmission is
given by the formula

$$0.1s \leq \lambda \leq 5s;$$

where λ is the wavelength of the transmission through the
overburden and s is the distance from the seabed to the
reservoir. More preferably λ is from about 0.5s to 2s.
The transmission frequency may be from 0.01 Hz to 1 kHz,
preferably from 1 to 20 Hz, for example 5 Hz.

In a preferred regime, a first transmission is made
at a first frequency and received by each receiver in a
tuned array of receivers, then a second transmission is
made at a second frequency and received by the same tuned
array of receivers, the receivers being tuned to receive
their respective transmission. This would probably be
repeated several more times, though it may only be carried
out once.

Preferably, the analysis includes comparing the
results of the measurements taken with the results of a
mathematical simulation model based on the known
properties of the reservoir and overburden conditions.

Preferably, the distance between the transmitter and
a receiver is given by the formula

$$0.5 \lambda \leq 1 \leq 10 \lambda;$$

where λ is the wavelength of the transmission through the
overburden and l is the distance between the transmitter
and the first receiver.

Given that the distances and the geometry of the
reservoir will be known from previous seismic surveys, an
optimum λ and l would be selected.

5   Preferably, the analyzing means is arranged to
analyze phase and amplitude. The data can be analyzed
using time domain and frequency domain techniques, and
other pulse sharpening techniques. Thus, the data can be
made to mimic seismic data so that conventional seismic
10   post-processing techniques can be employed.

If a location of interest is considered, a
mathematical modeling operation may be carried out. Thus,
the various relevant parameters, such as depth and
expected resistivities of the various known strata in the
15   overburden are applied to the mathematical model and the
expected results are calculated in dependence upon whether
a formation under consideration is oil-bearing or water-
bearing. The theoretically predicted results can then be
compared with the actual results achieved in the field in
20   order to determine the nature of the formation.

The present invention also extends to a method of
surveying subterranean measures which comprises;
performing a seismic survey to determine the geological
structure of a region; and where that survey reveals the
25   presence of a subterranean reservoir, subsequently
performing a method as described above.

The invention may be carried into practice in various
ways and some embodiments will now be described by way of
example with reference to the accompanying drawings, in
30   which: -

Figure 1 is a schematic diagram of an experimental
technique verifying the principles of the invention.

Figure 2 is a schematic section of a system in

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accordance with the invention.

Figure 1 shows a test rig comprising a tank 11 filled with seawater and a simulated oil-bearing layer, in the form of a diaphragm 12 filled with fresh water. The diaphragm 12 is suspended above the bottom of the tank 11. A transmitter 13 and a receiver 14 are mounted on respective vertical posts 15, 16 suspended from a beam 17. The posts are at a constant spacing L and the transmitter 13 and receiver 14 are vertically movable up and down their posts 15, 16.

When the transmitter 13 and receiver 14 are in the position shown in solid lines, the sensitivity of the receiver is adjusted so that the attenuation in the seawater is such that the direct wave 18 cannot be detected. Clearly, the reflected wave 19 would also be attenuated so much that it also would not be detected, given the greater distance of travel through the sea water.

The transmitter 13 and receiver 14 are then lowered down together, and transmissions made at intervals. At a particular depth indicated in broken lines, the receiver 14' detected a strong signal following a transmission from the transmitter 13'. This could not be a direct wave, nor a reflected wave, due to the attenuation by the seawater. It was therefore concluded that the only path for the wave to have taken was through the diaphragm 12. This is shown as a refracted wave 21.

The distance traveled through the seawater is relatively short and while the wave traveled some way through the fresh water in the diaphragm 12, the attenuation was considerably less than it would have been through the same distance in seawater. Thus, the overall attenuation was less than that for the direct wave 18 and the refracted wave 21 was detected.

A more practical example is shown in Figure 2. The
surface of the sea is shown at 31 with the sea 32
extending down to the ocean floor 33. There is an
overburden 34, an oil-bearing layer 35 and lower layer 36.
5   This structure is known from seismic surveys, but the
nature of the layers is not known. A transmitter is shown
schematically at 37 on the ocean floor 33 and a receiver
similarly at 38. They are spaced apart by an offset 39.

The transmitter 37 is in the form of a dipole antenna
10   which is arranged to transmit an electromagnetic wave
polarized in such a way that the radial E component is
generally along the line to receiver. This results in a
direct wave 41 being propagated in the sea water along the
surface of the overburden and a reflected wave 42a and 42b
15   which proceeds through the overburden 34, strikes the top
surface of the oil-bearing layer 35 and is reflected. The
portions which are received by the receiver 38 are
indicated.

The transmitted wave also results in a refracted wave
20   43. This is composed of a downward portion 43a which
descends through the overburden 34, a refracted protion
43b which travels along the layer 35, and an upward
portion 43c which travels back up through the overburden
34. Since the refracted portion 43b travels much faster
25   through the oil-bearing layer 35 and with far less
attenuation, the refracted wave 43 is detected first by
the detector 38 and at a relatively high signal level,
compared to the direct wave 41 and the reflected wave 42a,
42b.

30   The refracted wave 43 is particularly adapted for
determining the boundaries of an oil reservoir e.g. the
layer 35, if its depth beneath the ocean floor 33 is
known. This is due to the fact that the downward portion
43a of the refracted wave 43 mostly enters the layer 35 at

the critical angle, which is approximately 10° for an oil

bearing rock. At angles of greater than about 15°, total

reflection at the surface of the layer 35 occurs.

Thus, by adopting various positions for the receiver

5   38, the boundaries of the oil reservoir can be determined,

by the absence of an emerging refracted wave portion 43c,

with accuracy.

This technique also lands itself conveniently to

monitoring the changes in a reservoir, over a period of

10   time. The absence of a detected refracted wave will mean

that the boundary of the oil reservoir has moved and the

oil content depleted.

In the test layout shown in Figure 2, the seabed is

1000m thick, and has a resistivity of 2 ohm-m. The

15   hydrocarbon layer is about 50-100m thick and has a

resistivity of 50-100 ohm-m.

If the following parameters aree then selected:

Distance between the Tr antenna and the Re antenna =

4000m;   Frequency = 1.25 Hz; Transmitter antenna and

20   receiver antenna effective lengths L_T L_R = 500m (antenna

physical length 1000m). Transmitter current 200A.

Then the received signal (direct wave) will be about

$5 \mu V$. For f = 2.5 Hz, the received voltage becomes $0.5 \mu V$.

When the hydrocarbon layer has sufficiently large

25   width, one can expect that the refracted wave will be

stronger than the direct wave.

Claims:

1.   A method of determining the nature of a submarine or
subterranean reservoir whose approximate geometry and
5   location are known, which comprises: applying a time
varying electromagnetic field to the strata containing the
reservoir; detecting the electromagnetic wave field
response; seeking in the wave field response, seeking, in
the wave field response, a component representing a
10   refracted wave; and determining the content of the
reservoir, based on the presence or absence of a refracted
wave component.

2.   A method of searching for a hydrocarbon containing
15   subterranean reservoir which comprises: applying a time
varying electromagnetic field to subterranean strata;
detecting the electromagnetic wave field response;
seeking, in the wave field response, a component
representing a refracted wave; and determining the
20   presence and/or nature of any reservoir identified based
on the presence or absence of a refracted wave component.

3.   A method as claimed in Claim 1 or Claim 2, further
including the step of analyzing the effects on any
25   detected refracted wave component that have been caused by
the reservoir in order to determine further the content of
the reservoir based on the analysis.

4.   A method as claimed in any preceding Claim, in which
30   the applied electromagnetic field is polarized.

5.   A method as claimed in Claim 4, in which the
polarization is such as that the E-field component is
created by a horizontal dipole in the direction towards

the receiver.

6.   A method as claimed in any preceding Claim, in which the field is applied using one or more stationary transmitters located on the earth's surface.

7.   A method as claimed in Claim 6, in which a stationary transmitter is located in an existing well.

8.   A method as claimed in any preceding Claim, in which the detection is carried out by one or more stationary receivers located on the earth's surface.

9.   A method as claimed in any of Claims 6 to 8, in which the transmitter and/or receivers are located on or close to the seabed or the bed of some other area of water.

10.   A method as claimed in any preceding Claim, in which the transmitted field is in the form of a wave.

11.   A method as claimed in any preceding Claim, in which the field is transmitted for a period of time from 3 seconds to 60 minutes.

12.   A method as claimed in Claim 11, in which the transmission time is from 3 minutes to 30 minutes.

13.   A method as claimed in any of Claims 10 to 12, in which the wavelength of the transmission is given by the formula

$$0.1s \leq \lambda \leq 10s;$$

15

14

where λ is the wavelength of the transmission through the overburden and s is the distance from the seabed to the reservoir.

14. A method as claimed in any of Claims 10 to 13, in which distance between the transmitter and a receiver is given by the formula

$$0.5 \leq \lambda \leq 10S;$$

where λ is the wavelength of the transmission through the overburden and 1 is the distance between the transmitter and the receiver.

15. A method as claimed in any of Claims 6 to 14, in which the transmission frequency is from 0.01 Hz to 1 kHz.

16. A method as claimed in Claim 15, in which the transmission frequency is from 1 to 20 Hz.

17. A method as claimed in any of Claims 3 to 12, in which a first transmission is made at a first frequency and received by each receiver in a tuned array of receivers, then a second transmission is made at a second frequency and received by the same tuned array of receivers, the receivers being tuned to receive their respective transmissions, the transmitter(s) also being tuned for optimum transmission.

18. A method as claimed in any preceding Claim, which includes the step of comparing the results of the measurements taken with the results of a mathematical simulation model based on the known properties of the

reservoir and overburden conditions.

19. A method as claimed in any of Claims 13 to 18, which
includes suppressing the direct wave, thereby reducing the
required dynamic range of the receivers and increasing the
resolution of the refracted wave.

20. Apparatus for determining the nature of a
subterranean reservoir whose approximate geometry and
location are known, or for searching for a hydrocarbon
containing subterranean reservoir, the apparatus
comprising: means for applying a time varying
electromagnetic field to the strata containing the
reservoir; means for detecting the electromagnetic wave
field response; and means for seeking, in the wave field
response, a component representing a refracted wave,
thereby enabling the presence and/or nature of a reservoir
to be determined.

21. Apparatus as claimed in Claim 20, in which the means
for applying the field comprises a transmitter and the
means for detecting the field comprises an array of
receivers.

22. Apparatus as claimed in Claim 21, in which the
transmitter and the receivers comprise dipole antennae or
coils.

23. Apparatus as claimed in any of Claims 20 to 22, in
which there is more than one transmitter.

24. A method of surveying subterranean measures which
comprises; performing a seismic survey to determine the
geological structure of a region; and where that survey

17

reveals the presence of a subterranean reservoir, subsequently performing a method as claimed in any of Claims 1 to 19 to determine the nature of the reservoir.
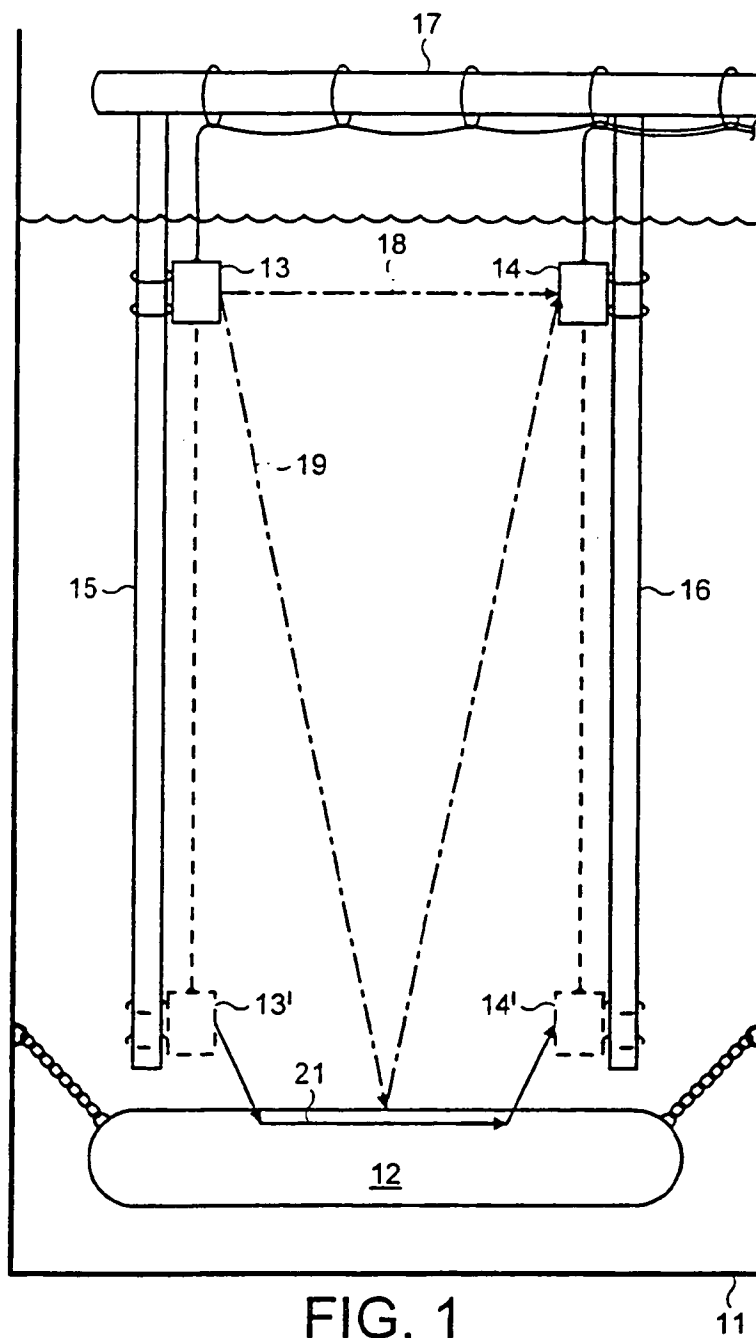
FIG. 1
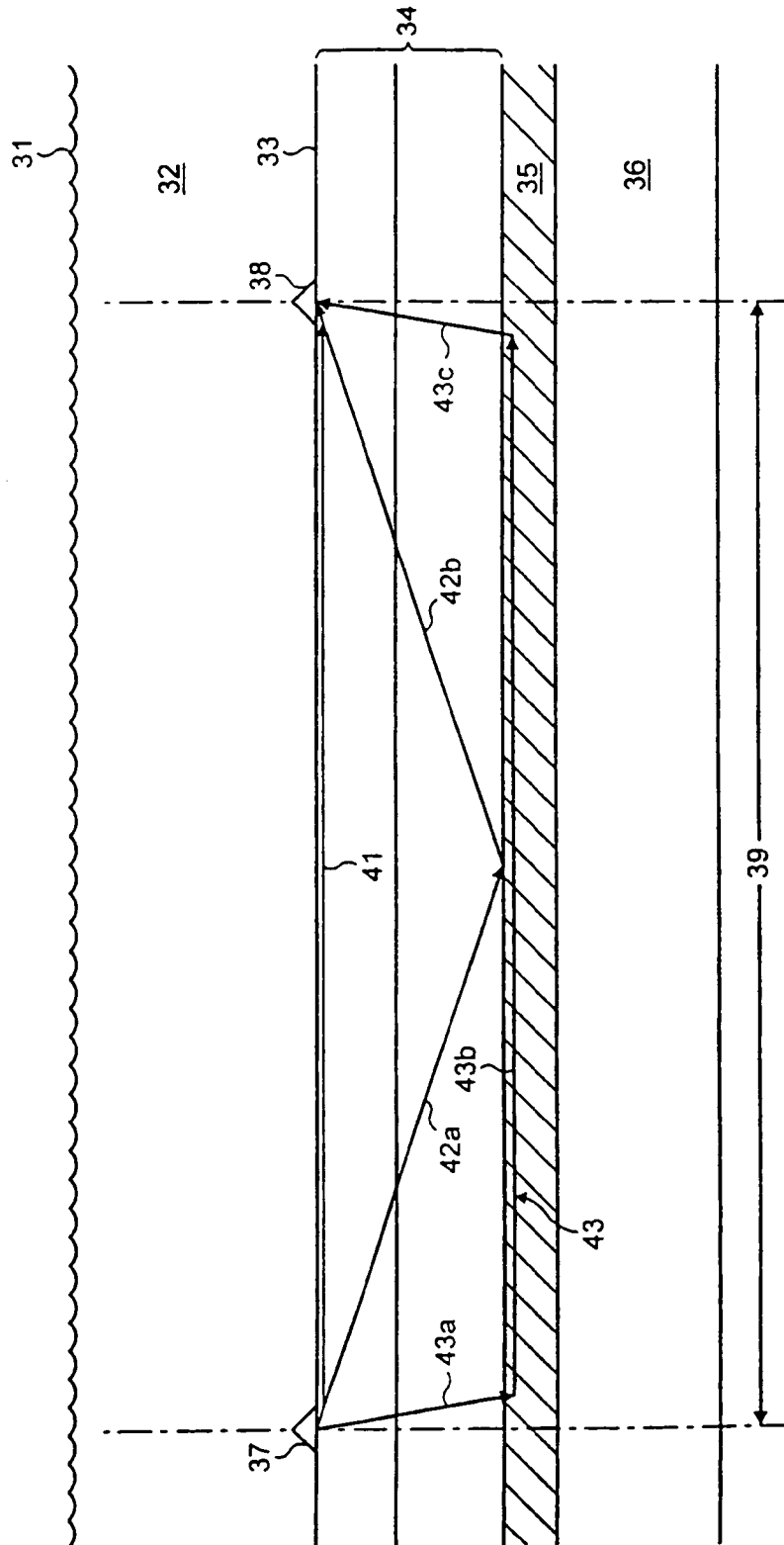
FIG. 2

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   G01V3/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 May 2001	17/05/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Schneiderbauer, K

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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